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Validation of Resistance Predictions Using Total Ship Drag (TSD)

by

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14. ABSTRACT
A robust computational tool has been under development at the Naval Surface Warfare Center, Carderock Division (NSWCCD) over the past several years to rapidly predict the resistance of ships, including high-speed ships and unconventional hull forms. The total ship drag (TSD) program utilizes slender ship theory to predict the wave-making resistance, the ITTC friction line to estimate frictional resistance, and adds several other components based on empirical data. The different components of resistance respond to changes in the hull form, which can be defined quickly using unstructured triangular elements. Some validation efforts have been carried out in the past. This report provides some further documentation of resistance validation of the TSD predictions compared with model test data for both monohulls and multi-hulls. In addition, for specific cases the TSD predictions are compared with other computational prediction methods. The TSD program also includes the ability to predict hull wave profiles and elevations of the wavefield caused by the wave-making of the ship. Some qualitative observations will also be provided here regarding these capabilities.
The current version of the code has been updated for inclusion in the CREATE-Ships Integrated Hydrodynamic Design Environment (IHDE) which is currently under development.

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Abstract

A robust computational tool has been under development at the Naval Surface Warfare Center, Carderock Division (NSWCCD) over the past several years to rapidly predict the resistance of ships, including high-speed ships and unconventional hull forms. The total ship drag (TSD) program utilizes slender ship theory to predict the wave-making resistance, the ITTC friction line to estimate frictional resistance, and adds several other components based on empirical data. The different components of resistance respond to changes in the hull form, which can be defined quickly using unstructured triangular elements. Some validation efforts have been carried out in the past. This report provides some further documentation of resistance validation of the TSD predictions compared with model test data for both monohulls and multi-hulls. In addition, for specific cases the TSD predictions are compared with other computational prediction methods. The TSD program also includes the ability to predict hull wave profiles and elevations of the wavefield caused by the wave-making of the ship. Some qualitative observations will also be provided here regarding these capabilities.

The current version of the code has been updated for inclusion in the CREATE-Ships Integrated Hydrodynamic Design Environment (IHDE) which is currently under development. This version is denoted as TSD10. Some of the predictions shown in this report utilize the IHDE to automate the mesh generation processs and make it quicker to perform the validation studies.

Administrative Information

The work described in this report was performed by the Computational Hydromechanics Division (Code 5700) of the Hydromechanics Department at the Naval Surface Warfare Center, Carderock Division (NSWCCD). The work was funded by a variety of sources over the past several years and contributions have been made to the code by several individuals. Preparation of this report was funded by the High Performance Computing Modernization Program (HPCMP) under work unit 11-1-5705-411.

Acknowledgements

The computational tool described in this report (TSD) has had a variety of people who have contributed to its development in the past. Most notably these include Dr. Francis Noblesse and Bryson Metcalf from the Hydromechanics Department at the Naval Surface Warfare Center, Carderock Division (NSWCCD) and Professor Chi Yang from George Mason University. Other persons have had significant use of the code, and their help and suggestions are appreciated. These include Ben Ruppel, Johnathan Slutsky, John Grabeel, Jesse Geisbert, and Steve Fisher. The CREATE-Ships IHDE development is primarily being performed by individuals from the Design Tools Development Branch (Code 223) including Rich VanEseltine, Tony Quezon, Ian Shields, and Bob Ames. The authors also acknowledge the support of the CREATE program with Myles Hurwitz as the lead for CREATE-Ships.

Introduction

Navy ships of the future may be radically different from those already in the fleet in order to meet emerging missions and related operational requirements. One difficulty with designing such new concepts is the lack of experience to draw from when performing design studies. These issues point to a need for greater fidelity, robustness, and ease of use in the tools used in early stage ship design. The Computational Research and Engineering Acquisition Tools and Environments (CREATE) program attempts to address this in its plan to develop and deploy sets of computational engineering design and analysis tools. It is expected that advances in computers will allow for highly accurate design and analyses studies that can be carried out during the early phases of the design process.

The primary goal of the CREATE-Ships Project is to develop the engineering software required to support a reconfigurable ship design and acquisition process that will enable the Navy to design and deliver ships on schedule and within budget, and that will perform as required and predicted. The customers include U.S. Navy (USN) stakeholder organizations which develop and manage ships and ship systems, individuals who use the wide range of computational tools in support of those stakeholders, and engineers and scientists developing computational tools in support of those users and stakeholders. Specific to hydrodynamics the effort will predict all hydrodynamic performance of a ship design at full scale and model scale to a level equal to that achievable with physical model testing and will not only transition a high-fidelity physics-based capability to the design process, but will also integrate that capability with lesser fidelity physics software. This will give ship designers the ability to make decisions early in the design process. The vehicle that is being developed to effectively make use of High Performance Computing in the earliest design stages is the Integrated Hydrodynamics Design Environment (IHDE).

The IHDE is a process-oriented capability that will integrate, primarily via the Navy ship community's product model capability Leading Edge Architecture for Prototyping Systems (LEAPS), a suite of hydrodynamics analysis software that includes a broad range of analysis types across a range of levels of physics fidelity. The primary purpose of the IHDE is to significantly expedite the processes associated with early-stage ship hydrodynamics analyses ranging from access to data for problem set-up, to automated submittal of large numbers of analyses to HPC systems, and to verification and validation of results against available test data.

One of the key design parameters in any ship design is the resistance. In the area of hydrodynamic prediction tools, one of the tools selected for inclusion in the IHDE is Total Ship Drag (TSD), which has been developed over a number of years at the Carderock Division of the Naval Surface Warfare Center. Recent efforts have been made to document the code and to provide validation information for applicable hydrodynamics problems. This report provides some of the background information on the development of TSD and gives the results of specific validation efforts for surface ship predictions.

Total Ship Drag (TSD)

TSD (total ship drag) is a robust fast resistance prediction tool appropriate for early stage design developed by researchers at the Carderock Division Naval Surface Warfare Center (Metcalf et al. 2004). This code is the successor to the EPPAC code, which was judged as one of the superior predictive tools from the "Wake-off" (Lindenmuth, Ratcliffe, and Reed, 1998). The total drag of a ship as calculated by TSD is made up of the following components: wave-making resistance, frictional resistance, form resistance, transom drag, and other drag. Each resistance component is estimated in a way that is faithful to the physics of the problem. The wave-making resistance is computed using slender ship theory (Noblesse, 1983). The frictional resistance is estimated using the ITTC friction line. Form resistance is approximated from Series 58 data. Transom drag is divided into two components—a base drag component which is modeled based on empirical data from sub-sonic bullet tests, and a hydrostatic component which accounts for the missing hydrostatic pressure on a dry transom. Finally, an additional component of drag is modeled which accounts for other drag sources such as spray. This component is empirically based on Series 64 data and other forms with spray formation. All these components of drag respond to changes in the hull form. Some additional code improvements have been made to integrate the TSD analysis tool into the CREATE IHDE. This version is delineated as TSD10 and is used for all of the predictions shown in this report.

TSD can be operated in two different modes. These are determined by a user-specified parameter (kext), which sets the relative importance of speed vs. accuracy. In the fast mode (Mode 1), it computes Noblesse's zeroeth-order slender-ship approximation to the far field wave resistance where the source strength applied on a panel depends only on the x-component (flow direction) of the normal to the panel. In the slower, more accurate mode (Mode 2), the zeroeth-order flow is computed at each panel on the hull. A local correction to the normal flow through the panel is then applied to the source strength at each panel before computing the wave resistance. This correction can be applied iteratively, but it is much more sensitive to panelization and is not guaranteed to converge.

Validation Strategy

This report will focus on results related to linear resistance predictions. The analysis capability has been divided into two separate areas: (1) linear resistance analysis for monohulls and (2) linear resistance analysis for multi-hulls. The Carderock Division of the Naval Surface Warfare Center is one of the leading hydrodynamic model test facilities; hence, a large amount of experimental data is available to use for validation. In addition, researchers at NSWCCD have been performing detailed hydrodynamics predictions of surface ship flow using Reynolds Averaged Navier-Stokes (RANS) solvers for many years. These two sources of data (i.e., model test measurements and previous high fidelity hydrodynamic analysis) are used for validation of the TSD predictions (in some cases run using the CREATE IHDE) in the following sections.

Results of Validation Testing

This section will provide results and discussion rclated to thc validation of TSD for both monohull and multi-hull ship configurations.

Linear Resistance Predictions for Monohulls

This scction provides results from the linear rcsistance validation tests. The first section provides validation for monohull ship configurations. The first casc involves comparisons with model test data and previous RANS predictions for the Joint High Speed Sealift (JHSS) ship concept. The experimental data was collected at NSWCCD (see Cusanelli, 2006). This is the baseline shafts & strust (BSS) configuration, denoted Model 5653. Other tests of the JHSS conccpt have included waterjet propulsion. The Model 5653 series of experiments also includcd resistance measurements for several different bow variants, and for scveral diffcrent displacemcnts. Thc bow variants included (1) stem bow, (2) baseline bulb (BB), (3) clliptical bulb (EB), and gooseneck bulb (GB). The displacements were varicd between the design displacement by +/- 10% yielding Heavy (HVY), Design (DES), and Light (LITE) for each bow variant. Some photographs of the JHSS hull concept model are shown in Figure 1. Thc first two cases uscd for validation in this report correspond to the JHSS Bascline Bulb (BB) and JHSS Gooseneck Bulb (GB) variants.

Thc third case that is used for validation in this report is the DTMB Modcl 5415. This is a pre-contract dcsign for the DDG 51 Arleight Burke destroyer class hull form. This modcl has been used extensively for validation by a variety of organizations for a number of ycars. The Modcl 5415 hull is shown in Figure 2.

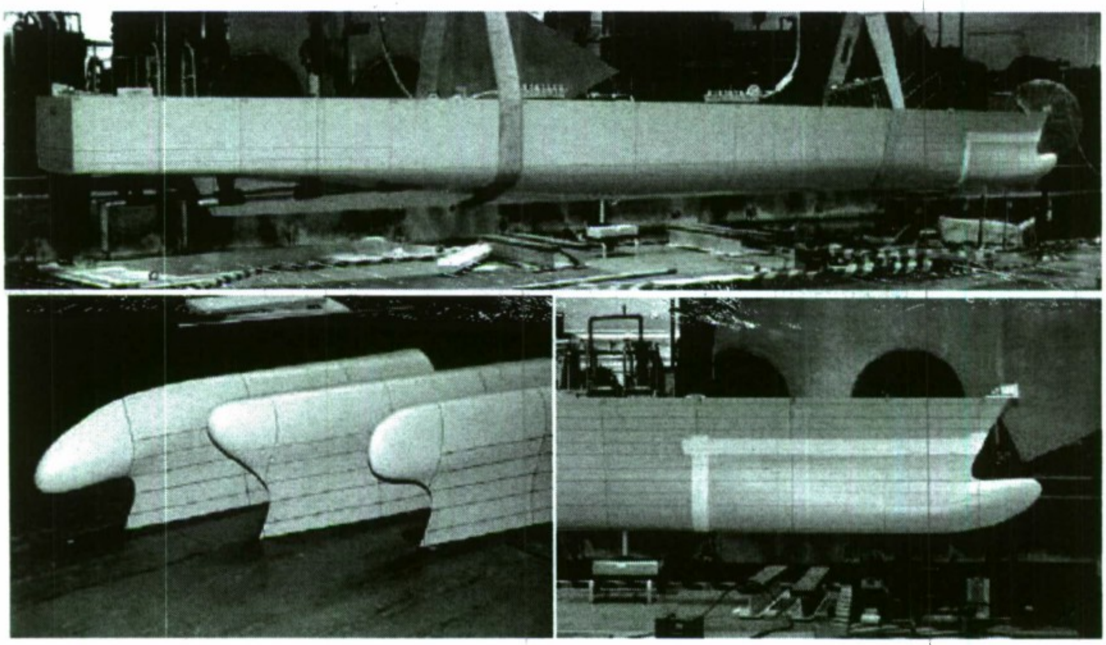


Figure 1. Photographs of JHSS Model 5653 and bow variants.

Figure 2. DTMB Model 5415 (profile view).

Case 1: JHSS, Baseline Bulb

Bare hull simulations using IHDE v2 have been compared with experimental data. In this case, the bare hull configuration includes the skeg. This configuration for the JHSS Model 5653 includes the baseline bulb bow variant. In this case, the predictions are performed for a full-scale ship modeled after Model 5653. Comparison of predicted resistance with measured values from the tests is given in Figure 3. Note, the experimental data was scaled up to full-scale as is often customary. The three different TSD10 predictions are for three different mesh densities. As shown in the figure, there is quite reasonable agreement between the predictions using TSD10 in the IHDE and the model test data (scaled up to full-scale Reynolds numbers). Separately, these results have been compared with predictions made using TSD10 external to the IHDE to ensure the integrity of the solutions.

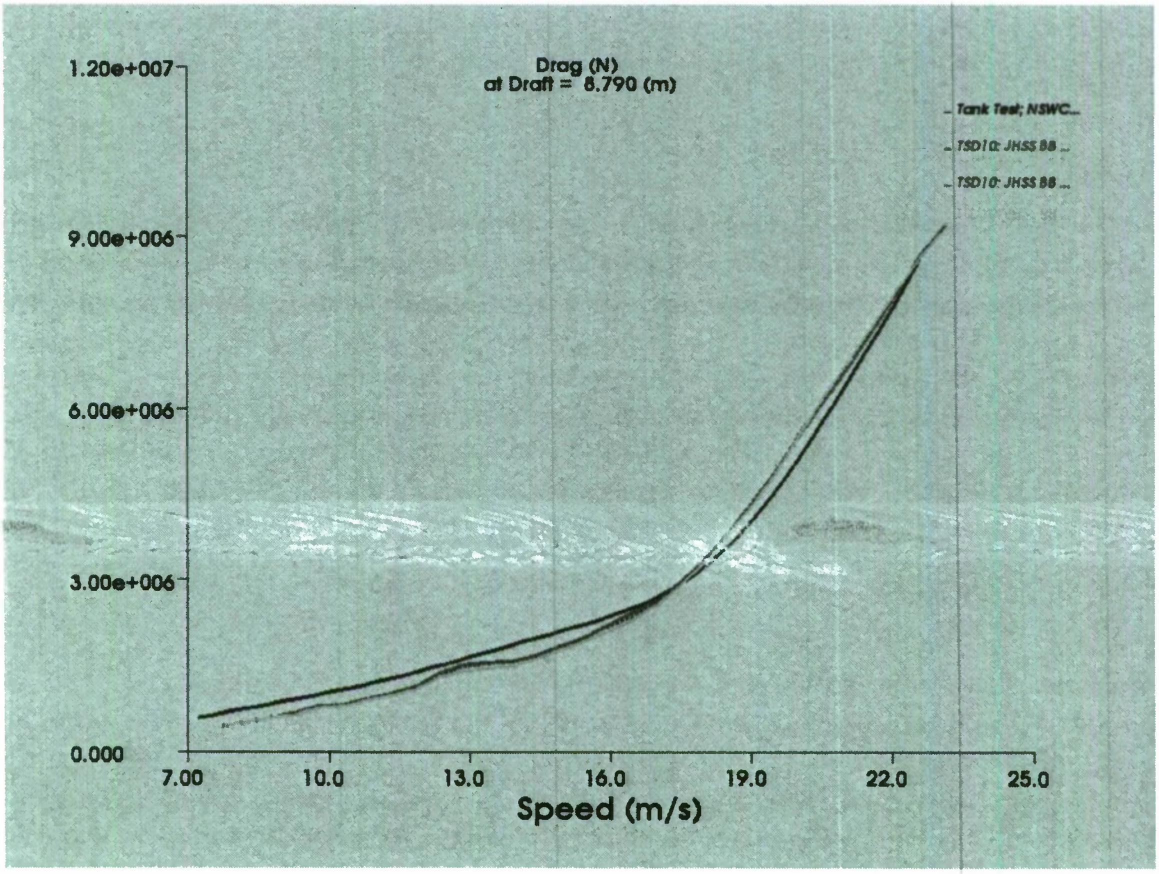


Figure 3. Total Resistance vs. speed, JHSS Full-Scale Baseline Bulb

The three different mesh densities used in the calculations are shown in Figure 4. These correspond to Grid 1, Grid 2, and Grid 3 in Table 1. As shown in the figure, each includes only the hull discretization used for the TSD calculations, which is after the waterline cut has been made at the appropriate draft. Each successive grid shows an increase in the overall mesh density as controlled by the mesh parameters in the IHDE mesh panel.

Figure 4. Hull discretizations used for TSD10 predictions in IHDE for three different mesh densities, corresponding to for JHSS Model 5653 Baseline Bulb at design displacement.

Table 1. Mesh comparison study parameters for JHSS Baseline Bulb (BB).

Grid #	Max Angle	Max AR	Max Pcurve	#Triangles
1	5	2	4.5	9,088
2	3	2	2.9	16,725
3	2	2	2.5	27,935

A comparison of the total resistance coefficients (as opposed to the total resistance) is shown in Figure 5. Again, the predictions using TSD in IHDE are compared with the experimental measurements, along with additional simulations performed using a Reynolds-Averaged Navier-Stokes solver, CFDShip-Iowa. Again, this shows reasonable comparisons with both the experimental fluid data (EFD) and with the RANS (CFD) predictions, but does more clearly indicate the differences, which can sometimes be overlooked when comparing only the total resistance.

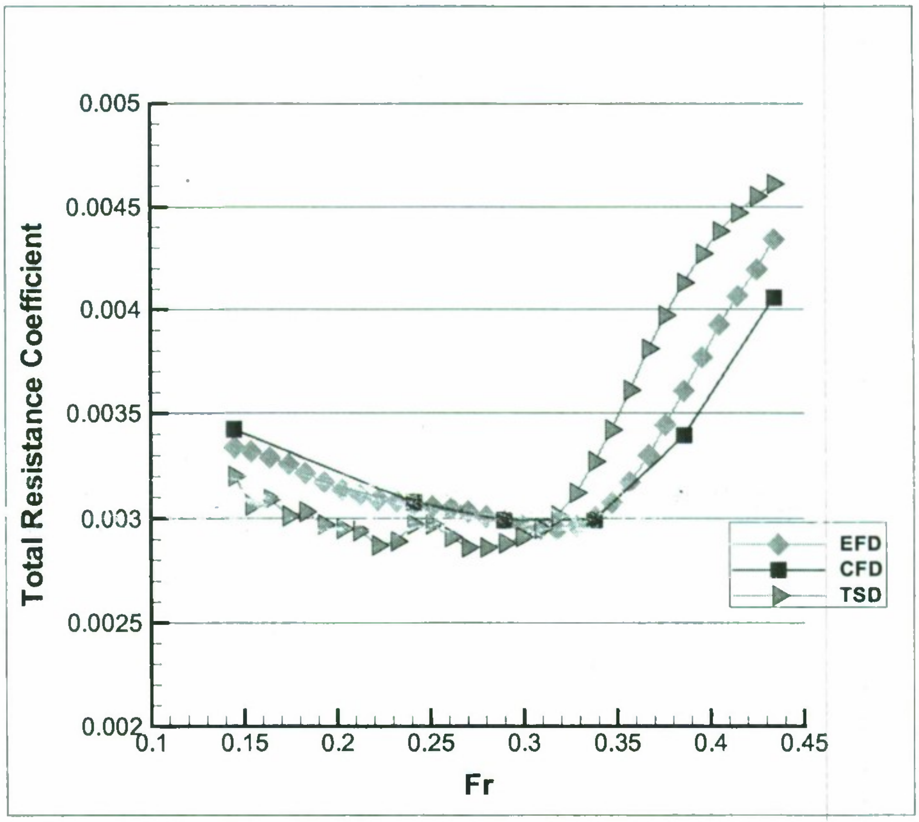


Figure 5. Predicted total resistance coefficient using TSD and CFDShip-Iowa (CFD) vs. experiment (EFD) for JHSS Model 5653 Baseline Bulb (Full-scale).

A sensitivity study was conducted to examine the influence of the mesh density on the predictions for the total resistance coefficient. Three separate predictions were performed using the IHDE for three different mesh densities. The mesh density is controlled using several parameters. These are the maximum angle (which controls how the mesh is adjusted to account for curvature on the model) the maximum aspect ratio (AR), which is generally set to 2.0, and the maximum "pcurve" length (which sets the largest mesh element length scale). The mesh parameters and associated mesh sizes are shown in Table 1. The predicted total resistance coefficient associated with each of these meshes is shown in Figure 6. For accuracy mode 1 (zeroth order), the predicted resistance shows little sensitivity to the mesh density. This has been demonstrated for other cases as well.

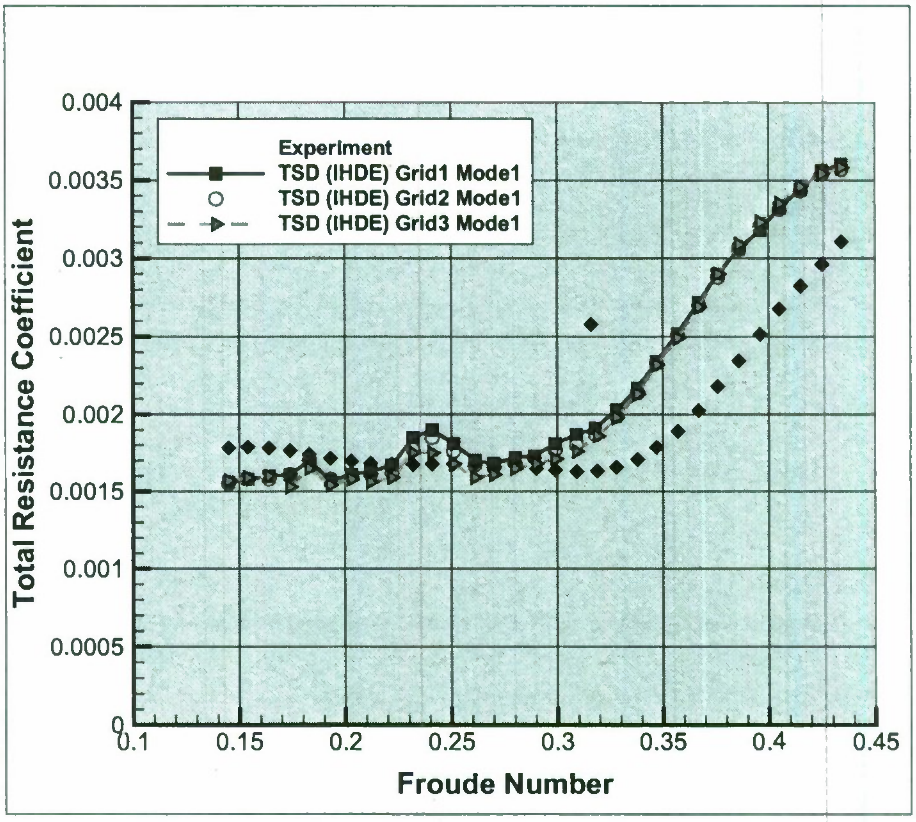
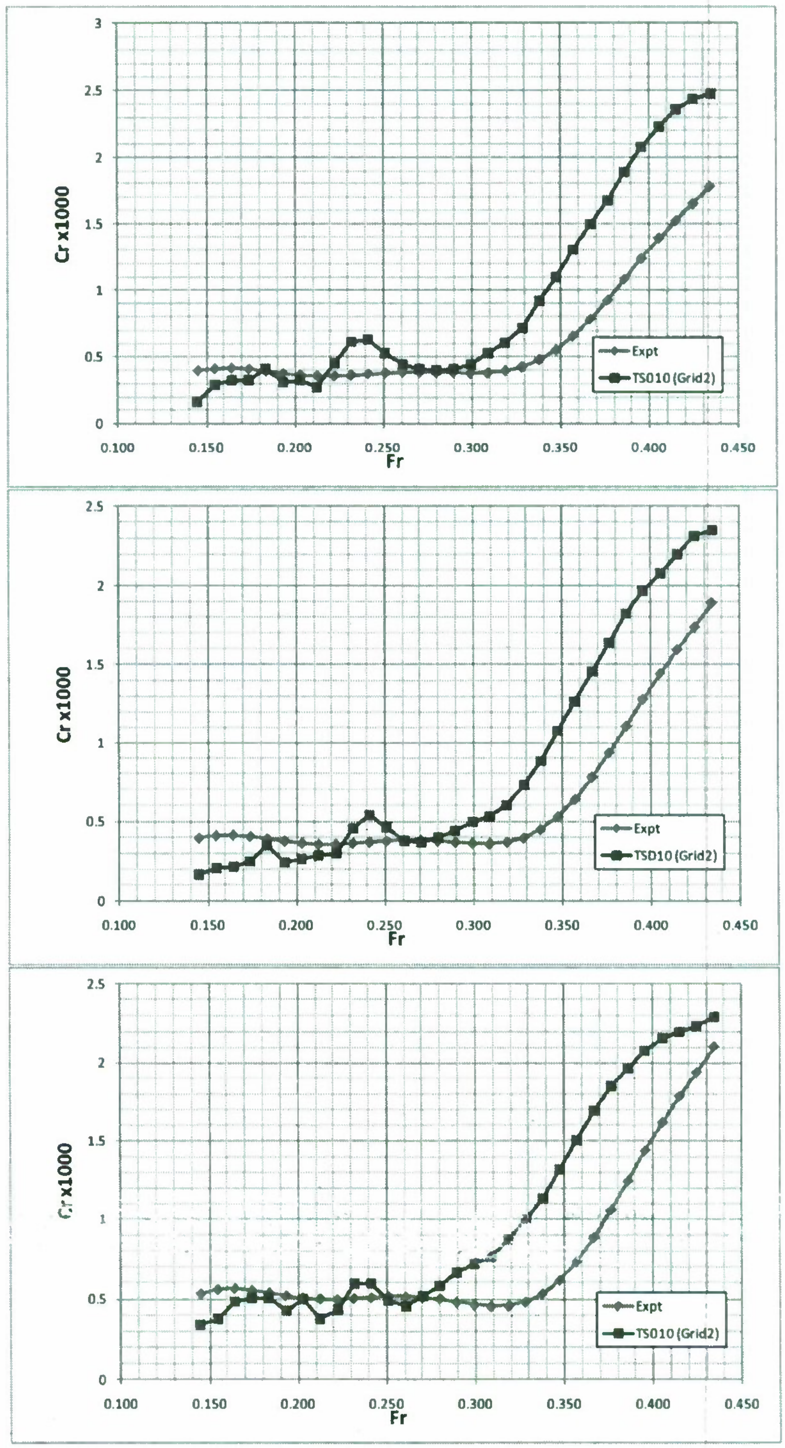


Figure 6. Total resistance coefficient vs. Fr (JHSS BB Full-Scale): Influence of computational mesh.

The model test data also includes measurements at different displacements. Each bow variant of the hull configuration was tested at the design displacement (DES) and a light (LITE) displacement corresponding to -10% of design displacement and a heavy (HVY) displacement corresponding to a +10% increase from the design displacement. Several comparisons are made for the predicted residual resistance coefficient (C_r) with the experimental measurements for each displacement in Figure 7. The comparisons with the experimental data shows reasonable agreement for all three displacements. It should be noted here that as the Froude number increases, it is expected that there may be inaccuracies due to the increasing nonlinear behavior of the wave field.



(a)

(b)

(c)

Figure 7. Predicted residual resistance coefficient (Cr) for JHSS BB compared with experimental data at three different displacements:

(a) Light (LITE), (b) Design (DES), (c) Heavy (HVY)

A comparison of the predicted C_r for all three displacements using TSD is shown in Figure 8. This demonstrates the ability of the code to predict changes in the resistance as a function of changes in the draft, even for high Fr.

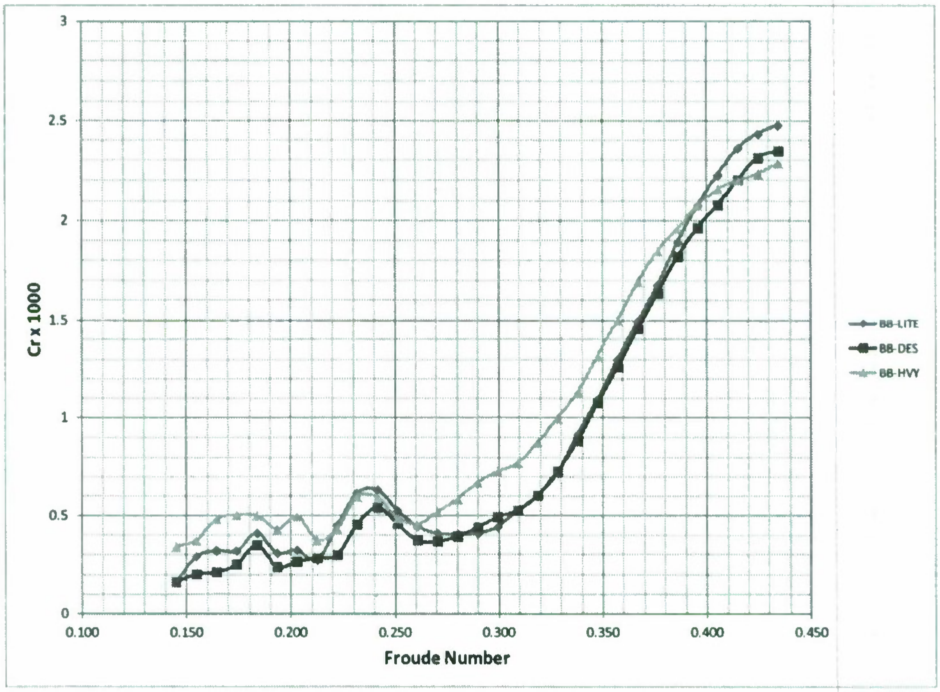


Figure 8. Comparison of the TSD predicted residual resistance coefficient (Cr) for all three displacements of JHSS Baseline Bulb.

The TSD tool can also determine the hull wave profile as a function of speed and draft. The predicted hull wave profile for the design speed of 36 knots and the design displacement is shown in Figure 9. A quantitative comparison with experimental measurements of the wave profile along the hull is shown in Figure 10. The wave height is full-scale feet from the ship baseline. The comparison with measurements shows reasonable prediction of the basic trend in the wave profile, though the bow wave height is somewhat underpredicted. Results using two different grid densities show little influence on the wave profile.

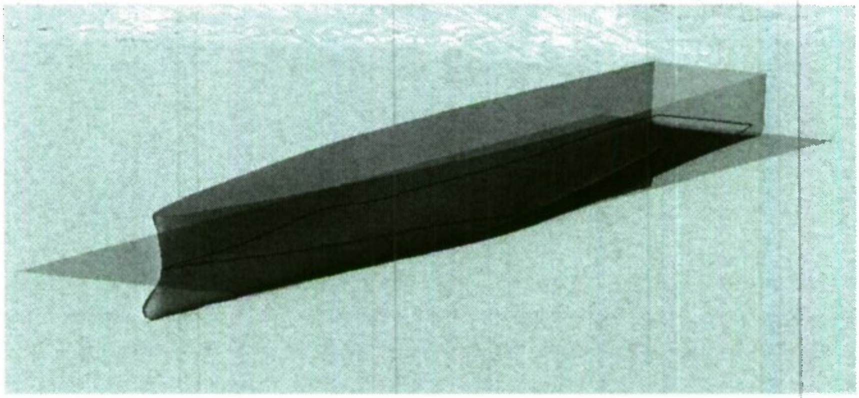


Figure 9. Hull wave profile, JHSS Full-Scale Baseline Bulb (Design Displacment, 36 kts).

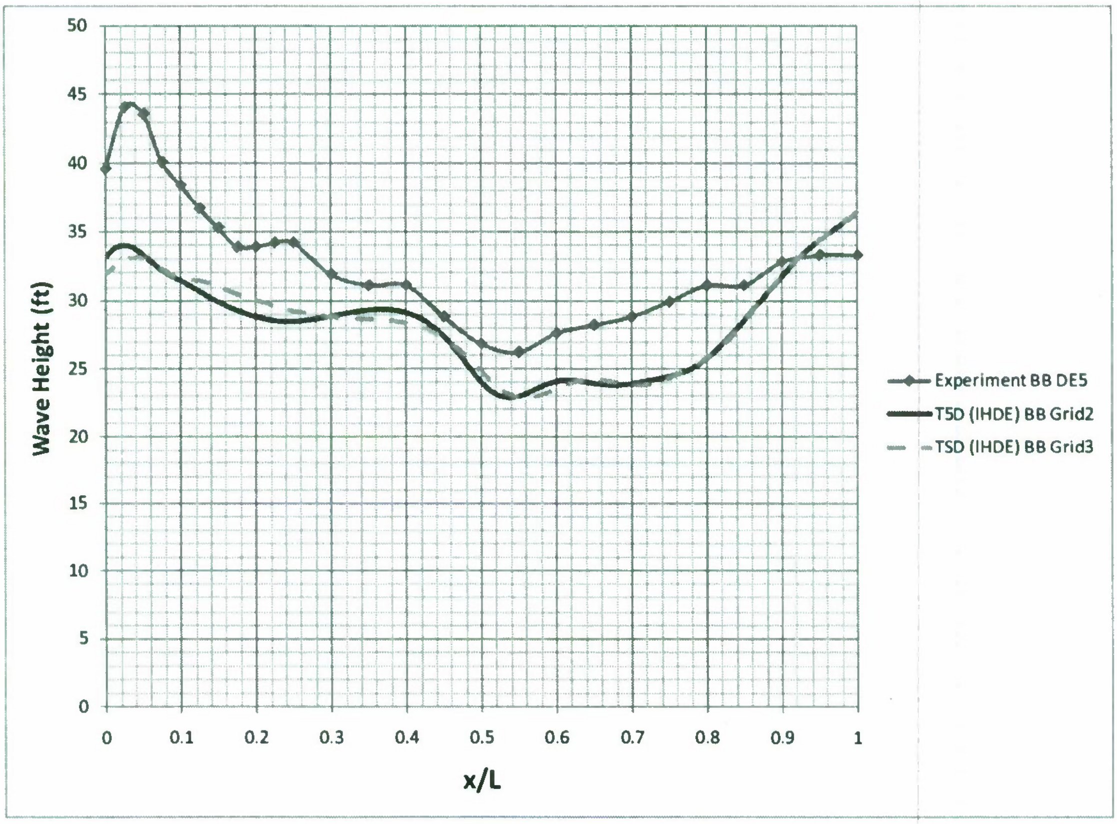


Figure 10. Predicted wave profile along the hull for JHSS BB at design displacement and design speed.

In a separate set of analyses, it is also possible to utilize the TSD10 tool within IHDE to predict the free surface wave elevations as a function of speed and draft. These are shown in Figure 11 for four different speeds at the design displacement and demonstrate a way to examine the influence of ship speed on the free surface wave field.

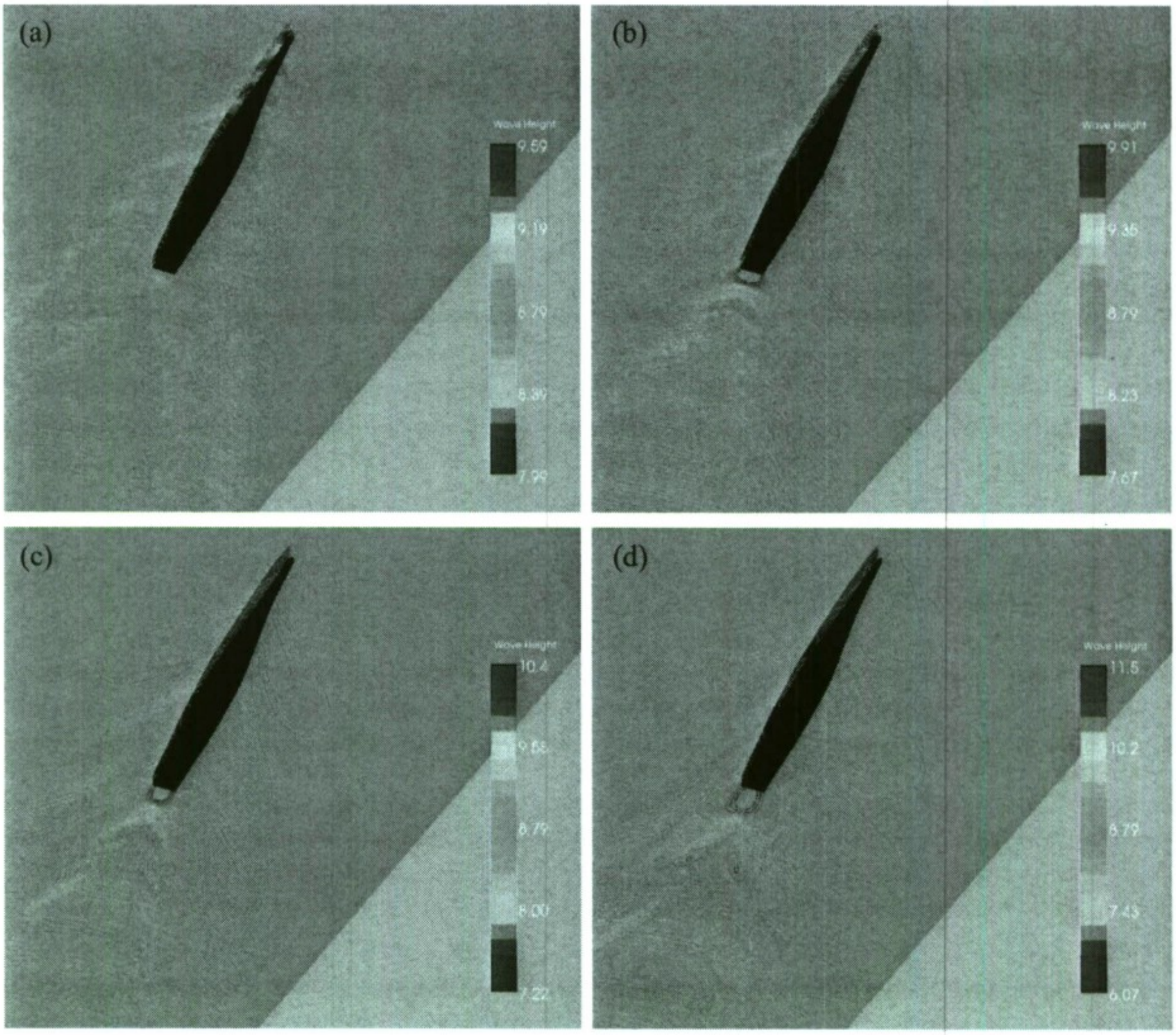


Figure 11. Predicted Free Surface Elevations: (a) 20 kts, (b) 25 kts, (c) 30 kts, (d) 36 kts.

Case 2: JHSS, Gooseneck Bulb

A similar set of predictions was made using the gooseneck bulb (GB) bow variant from the Model 5653 tests. A comparison of the predicted total resistance as a function of the ship speed is shown in Figure 12. Again, the TSD10 predictions are made for several different mesh densities. As shown in the figure, there is again quite good agreement between the total resistance predictions made using TSD10 and the model test data.

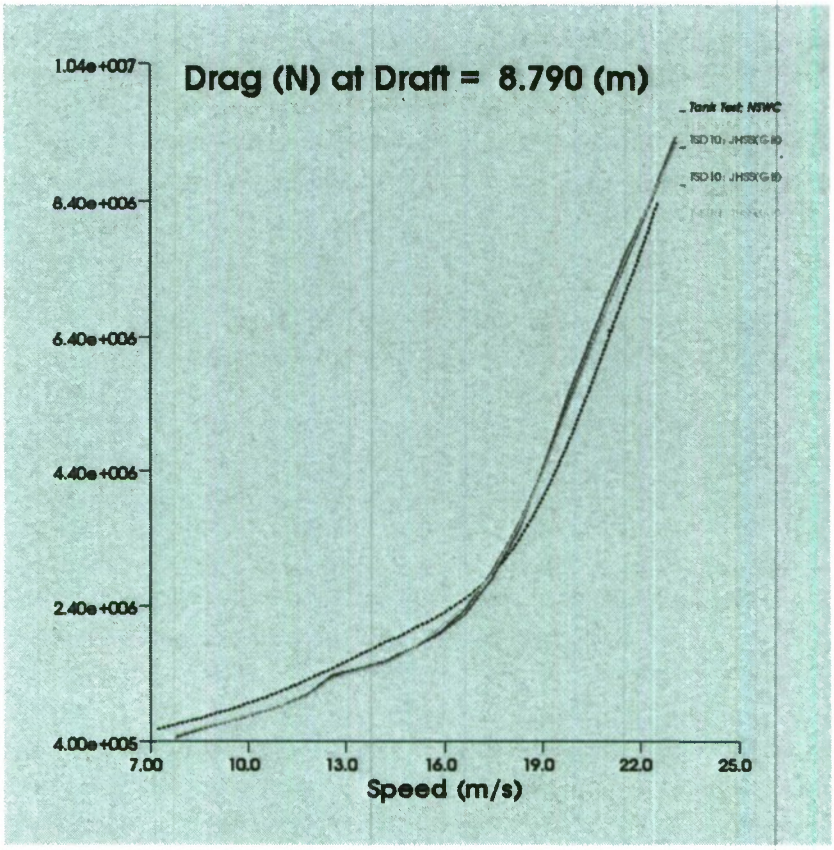


Figure 12. Total resistance vs. speed, JHSS Full-Scale Gooseneck Bulb (from IHDE).

As in Case 1 for the baseline bulb, the effect of displacement was again examined by comparing with experimental data for the light, design, and heavy displacement cases for the gooseneck bulb. This comparison is shown in Figure 13. The results in the figure show similar agreement as for the baseline bulb between the predicted resistance and what was measured in the experiments.

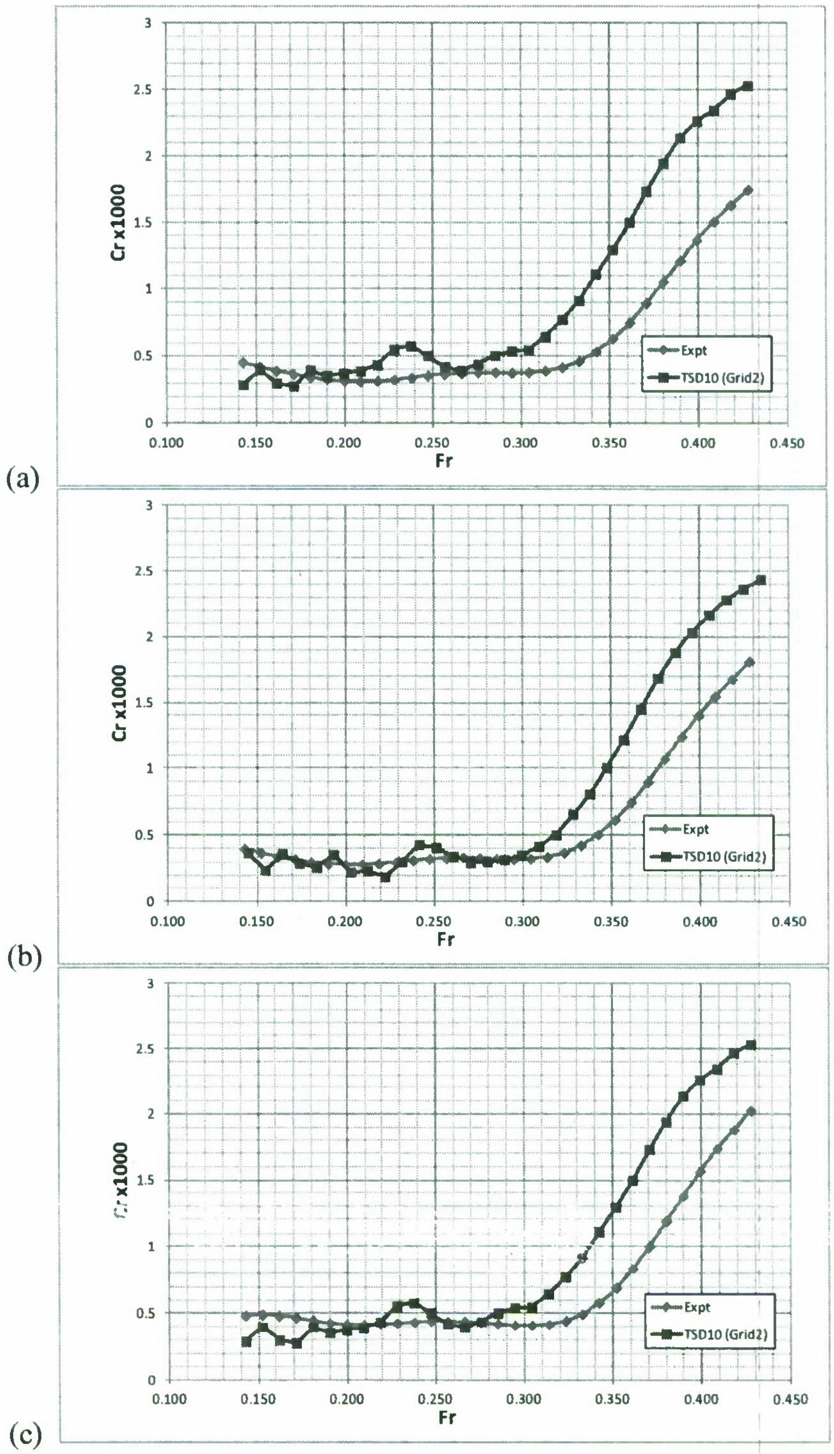


Figure 13: Predicted residual resistance coefficient (Cr) for JHSS GB compared with experimental data at three different displacements:

(a) Light (LITE), (b) Design (DES), (c) Heavy (HVY)

Case 3: Model 5415

A very commonly used ship hull configuration for validation of numerical predictions is the DTMB Model 5415. This is a pre-contract design for the DDG 51 destroyer class hull form. The Model 5415 was included in a LEAPS database along with experimental data collected at NSWCCD for resistance (see Lin, 1982). The model was simulated in IHDE using TSD10 and the results are shown in Figure 14. This figure was generated using the IHDE plotting feature. Here the black dotted line represents measurements taken at NSWCCD. The red and blue lines each correspond to the two operation modes available in TSD. For these comparisons the mesh was of moderate density, with approximately 10,000 panels defining the below-waterline surfaces, and by visual inspection the bow bulb was well represented. The hull panelization is shown in Figure 15. As shown in Figure 14 the predicted total resistance is in quite good agreement with the model test data with both modes of operation.

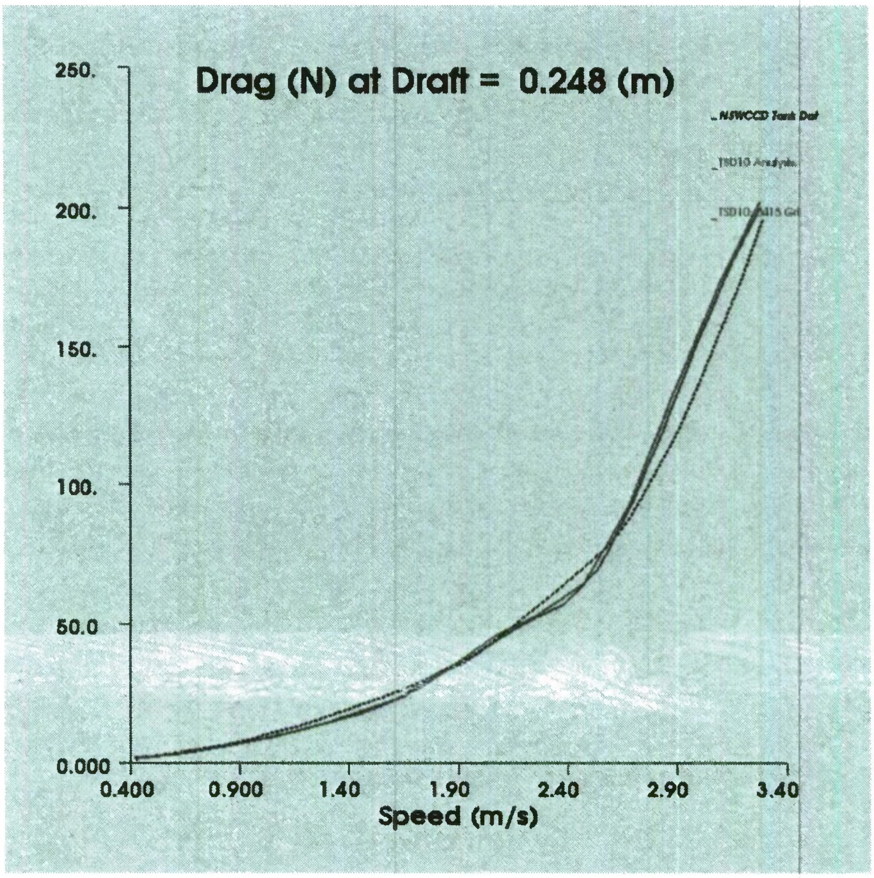


Figure 14. Predicted total resistance vs. speed for Model 5415 static trim (from IHDE).

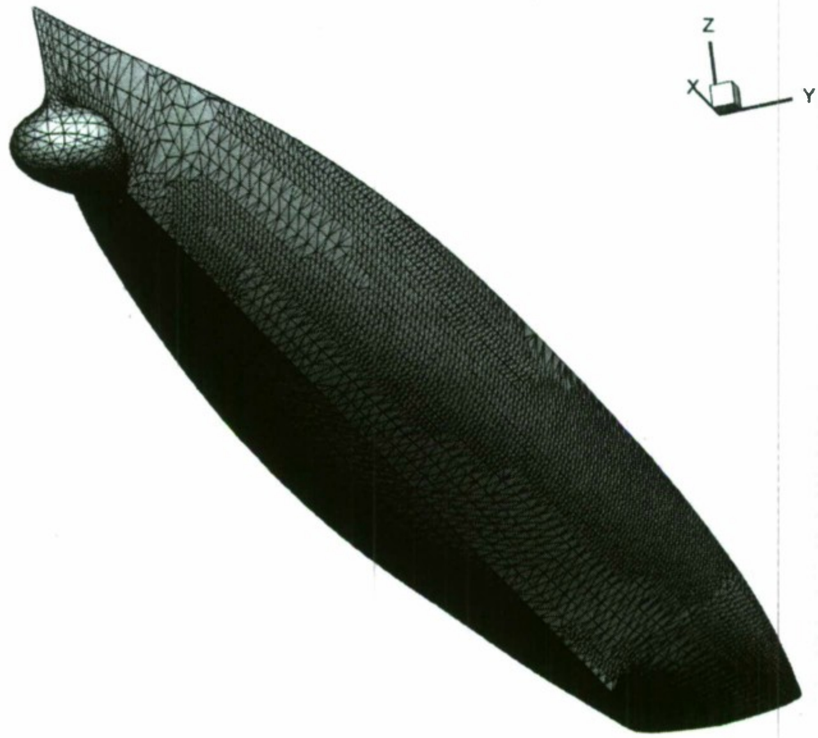


Figure 15. Hull panelization used for Model 5415 simulations in IHDE.

A grid sensitivity study was again carried out for the Model 5415 predictions. A comparison of the predicted total resistance coefficient as a function of Froude number for four different grid densities is shown in Figure 16 using Mode 1. A comparison with the experimental measurements shows that the TSD10 predictions in IHDE agree quite well with the measurements across the entire Froude number range. Additionally, there appears to be little influence of the mesh density on the results when using Mode 1, as was shown for the JHSS predictions.

A second comparison was made using Mode 2, which is the increased accuracy mode. This comparison is shown in Figure 17 Here there are some spurious results between Fr=0.3 and 0.4. This is likely due to the fact that care must be taken when using Mode 2 because the behavior is not guaranteed to be convergent. It is likely, then, that at some of the speeds predicted, the modification to the velocity field to improve the hull boundary condition may have been divergent in the first correction. This behavior is currently being examined, and a more robust method for utilizing the increased accuracy mode in TSD is planned for future development of the CREATE-Ships IHDE program.

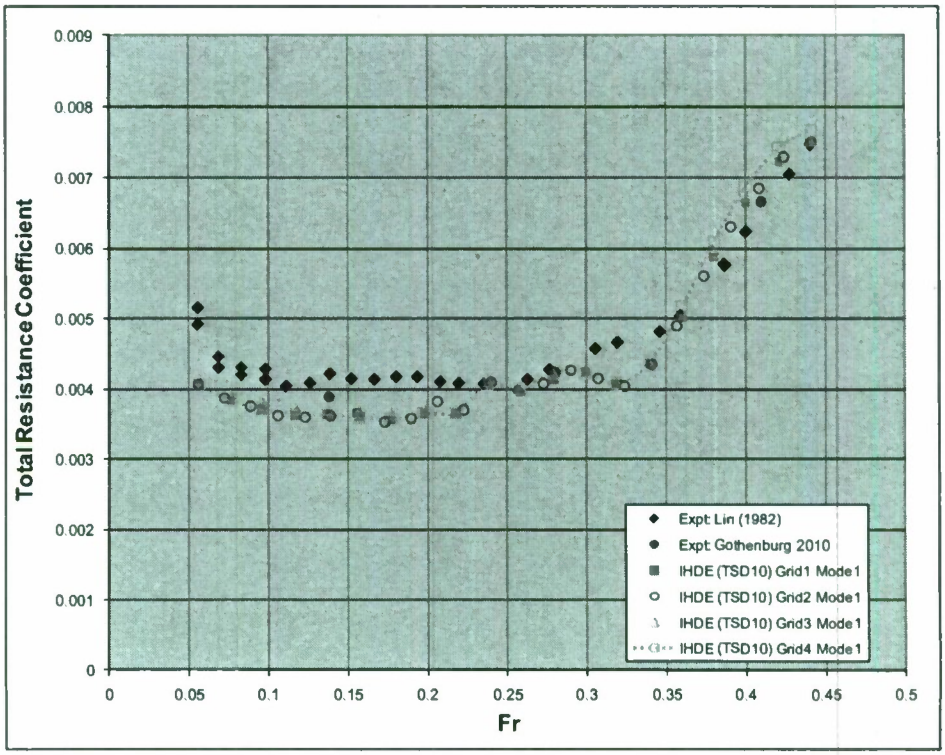


Figure 16. Total resistance coefficient vs. Fr (Model 5415): Influence of Mesh

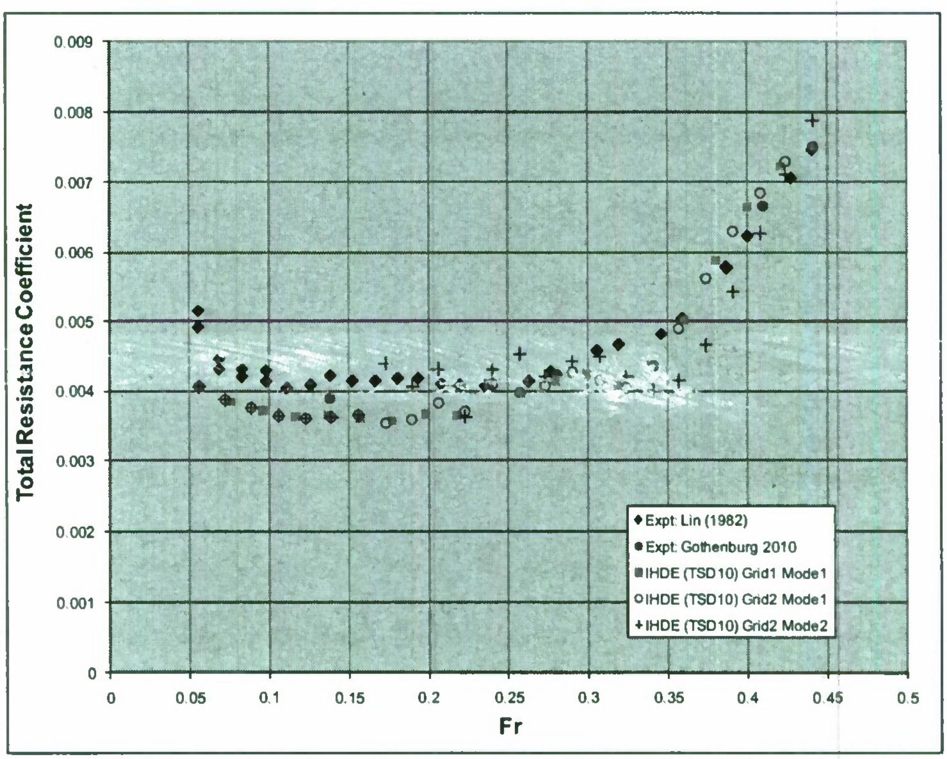


Figure 17. C_T vs. Fr (Model 5415): Influence of Accuracy Mode

Linear Resistance Predictions for Multi-Hulls

Case 4: Delft Catamaran

The fourth case used for validation is the Delft Catamaran. It is shown in Figure 18. This is a generic catamaran hull configuration that was tested at Delft University of Technology in 1998 (Van't Veer, 1998). This configuration has been examined by a number of researchers, and was used as part of the TSD validation testing for multi-hull configurations.

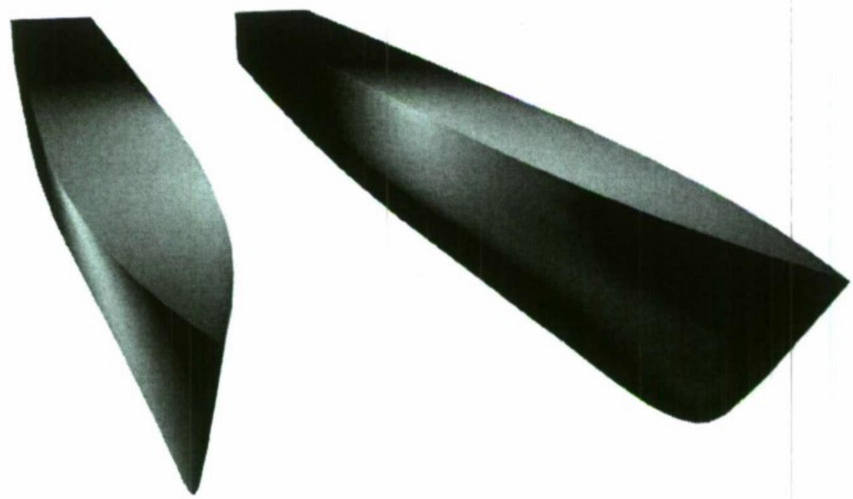


Figure 18. Delft Catamaran hull geometry (perspective view).

A grid comparison study was carried out to examine the sensitivity of the predictions to the mesh density. The IHDE was again used to facilitate the grid generation so that the study could be performed quickly. As part of the IHDE mesh generation process there are three different mesh control parameters. These are the maximum angle, the maximum aspect ratio (AR) and the maximum Pcurve length. By varying these three parameters, the user can roughly control the overall mesh density. In addition, there are two mesh generation methods available in the IHDE. These are the Superface method, and the advancing front method. In this example, the Superface method was used to carry out the mesh comparisons, but a single case was also generated using the advancing front method to see if there were any significant changes in the analysis as a result of the mesh generation method. All of the study parameters are given in Table 2 below.

Table 2. Mesh comparison study parameters for Delft catamaran.

Grid #	Method	Max Angle	Max AR	Max Pcurve	#Triangles
1	Superface	10	2	0.1	3,401
2	Superface	10	2	0.05	8,295
3	Superface	5	2	0.05	12,781
4	Superface	2	2	0.05	15,872
5	Superface	5	2	0.02	43,858
6	Superface	2	2	0.03	49,942
7	Advancing Front	5	2	0.03	21,808

Comparisons are made in Figure 19 for the predicted total resistance coefficient of the Delft catamaran bare hull model using mode 1 for a variety of different mesh densities. The predicted resistance coefficient is shown here to be quite insensitive to the mesh density when using mode 1. This is consistent with observations that have been made regarding the fast operation mode for other problems (e.g., Model 5415 predictions in previous section).

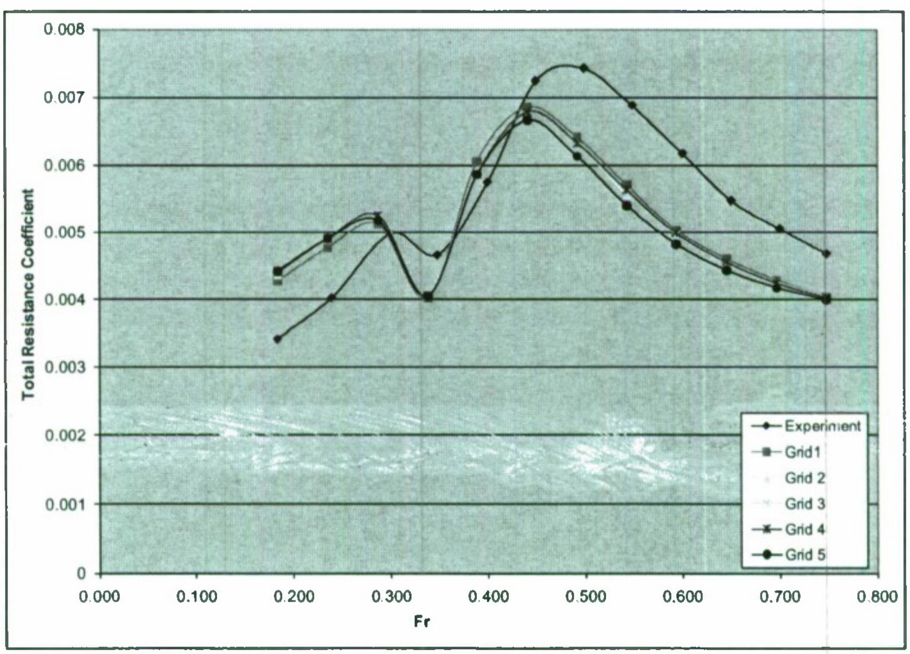


Figure 19. Total resistance coefficient of Delft catamaran (TSD Mode 1).

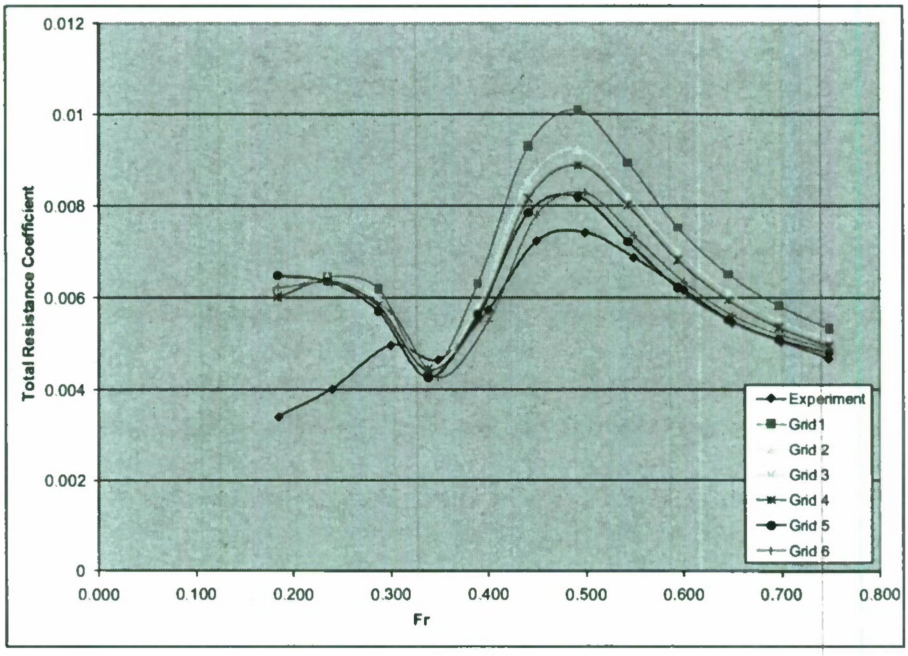


Figure 20. Total resistance coefficient of Delft catamaran (TSD Mode 2).

A similar comparison is made in Figure 20 for predictions using mode 2. By comparing Figure 19 and Figure 20 it is clear that the mode 2 results more accurately represent the total resistanee as a function of Froude number. In both eases there is a signifieant deviation from the experimental data at very low Froude numbers. This is not unexpected as the accuracy of the potential flow method becomes degraded for very low values of Fr. Also by examining Figure 20 we can see the influenee of the ehanges to the hull discretization as the finer grids produee solutions which asymptotically approach the model test data, particularly in the region around Froude number of approximately 0.5. Here grids 5 and 6 are elosest to the experimental data, and these grids are the finest used in this comparison. From this we can see how utilizing Mode 2 provides more accurate predictions for multi-hulls. This is due to the faet that applying an additional eorreetion to the hull boundary eondition begins to inelude the influence of the interferenee between the hulls, whieh is not aeeounted for when using Mode 1. It is therefore recommended to use Mode 2 for multi-hull predictions.

An additional eomparison is made in Figure 21 between the two grid generation methods available in the IHDE. Here the final result for Grid 7 using an advaneing front method is shown. By comparing the results, it appears that the solution results are largely insensitive to the grid generation method as well.

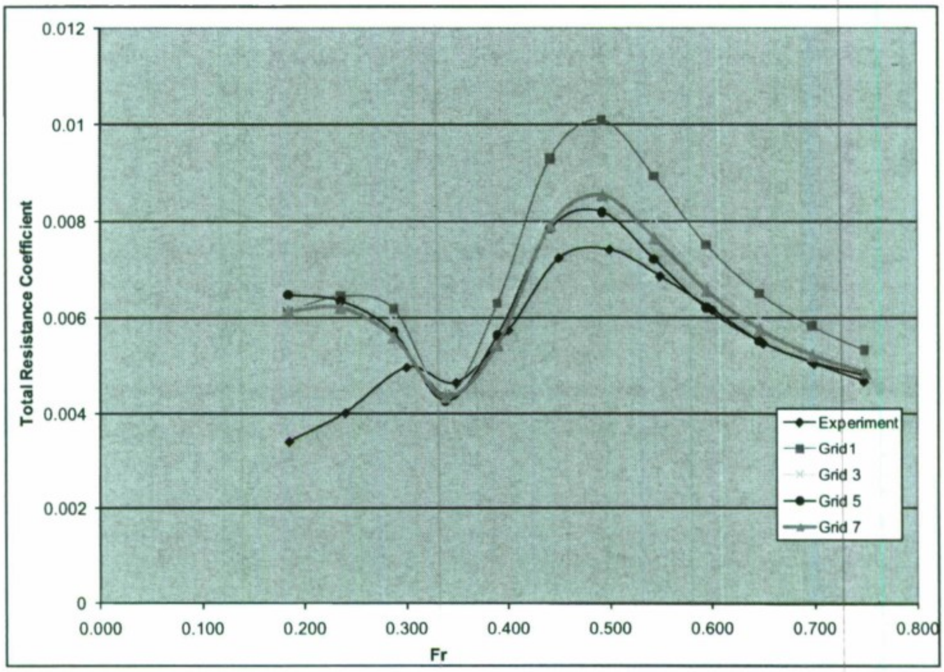


Figure 21. Comparison of Grid Methods for Delft Catamaran (TSD Mode 2).

Summary and Conclusions

This report documents several validation tests performed using the linear resistance analysis tool TSD10. In many cases the CREATE-Ships Integrated Hydrodynamic Design Environment (IHDE), which is currently under development, has been used to efficiently generate computational meshes and compare the predicted resistance with experimental measurements, as well as to perform grid sensitivity studies. The TSD program includes two different accuracy modes (denoted Mode 1 and Mode 2), which have both been utilized as part of this effort. The primary difference is that Mode 2 includes an additional correction to the velocity field to improve the hull boundary condition. In many cases this should result in a better prediction of resistance; however, care must be taken when using Mode 2 due to the possibility that the solution may become divergent.

Several different ship hull forms were utilized for validation testing. These include a full-scale version of the Joint High Speed Sealift (JHSS) ship concept, represented by Model 5653. This model was tested using four different bow variants. For the purposes of validation testing two of these variants, the baseline bulb (BB) and gooseneck bulb (GB), were analyzed using TSD10 as implemented in the IHDE. The results indicate quite reasonable agreement with the experimental data, as well as the ability to properly distinguish the changes due to the bow shape.

DTMB Model 5415, a pre-contract DDG 51 class destroyer hull form, was also included for validation purposes, along with experimental data for resistance. Comparisons indicate quite good agreement between the TSD10 predictions in IHDE and the model test data. The

predictions do, however, point out an issue with the fact that care must be taken when utilizing the increased accuracy mode in TSD10 because the velocity field corrections may become divergent. A more robust means of handling the increased accuracy mode in TSD10 is planned for future versions of the CREATE IHDE.

In order to examine the ability to perform resistance predictions for multi-hulls, several predictions were performed for the Delft catamaran. This is a commonly used data set for code validation and academic exercises. The predictions made using TSD10 show reasonable agreement when using Mode 1. Also, as in the case of the JHSS predictions, the resistance appears to be fairly insensitive to refinements to the computational mesh. When using Mode 2, however, there is a marked improvement in the accuracy of the predictions. This is due to the fact that the additional velocity field correction to improve the hull boundary condition begins to take into account the interference effect between the hulls, which is not accounted for when using Mode 1. It is therefore recommended that Mode 2 be used when predicting the resistance of multi-hull configurations. For monohull configurations, Mode 1 has been demonstrated to be sufficiently accurate; therefore, it should be used for monohulls to avoid any divergence issues.

In general, these cases demonstrate that the linear resistance analysis using the total ship drag (TSD) program does a good job of providing quick and reasonably accurate evaluations for typical US Navy hull forms. These efforts also provide some examination of the relative accuracy of using slender ship theory methods in predicting resistance for relevant Navy hullforms, including both monohull and multi-hull configurations. The inclusion of TSD10, an updated version of TSD, in the CREATE-Ships IHDE provides a fast, robust method for predicting resistance during the early stages of ship design activities.

APPENDIX: TSD PROGRAM

The Total Ship Drag (TSD) software program is provided with this report on the attached CD.

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